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Digital Innovation and the Division of Innovative Labor: Digital Controls in the Automotive Industry

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In this study of the U.S. automobile industry, we highlight the way the division of innovative labor across firms in the supply chain can be influenced by a particular form of digital innovation known as "digital control systems." Digital control systems are becoming ubiquitous in complex products, and these digital innovations integrate other components across a product structure and introduce a level of indeterminacy and unpredictability in the organization of the interfirm division of innovative labor. Much of organizational scholarship holds that accompanying a shift toward increasingly modular product structures, component suppliers are engaging in relatively more design and invention around the components that they supply. We find that the evolution of digital controls may reverse this pattern, because in the wake of a major shift in the digital controls technology, suppliers actually engage in relatively less component innovation in comparison with their large manufacturing customers. To explain this shift, we characterize complex product structures in terms of two distinct product hierarchies: the inclusionary and the digital control hierarchy. In using this distinction to analyze the evolution of automotive emission control systems from 1970 to 1998, we reconcile two competing views about the interfirm division of innovative labor.

Key words: digital innovation; digital controls; mirroring hypothesis; division of innovative labor; systems integration; dual-product hierarchy; automotive industry; inclusionary hierarchy; digital control hierarchy
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Introduction

Contemporary complex product development takes place throughout supply chains, where diverse, specialized knowledge sources collaborate across firm boundaries (Von Hippel 1988, Powell et al. 1996, Inkpen and Dinur 1998, Helper et al. 2000, Van de Ven 2005). This "division of innovative labor" (Arora and Gambardella 1994) is becoming increasingly important to organizations because rapid advancements in information technologies and trends toward product modularization enable unprecedented levels of interorganizational design coordination (Brusoni 2005). Thus, there is growing attention to the division of innovative labor across a variety of traditions of organizational scholarship (e.g., Takeishi 2001, Brusoni and Prencipe 2006, Lichtenthaler 2008, Argyres and Bigelow 2010, Hoang and Rothaermel 2010).

The prevailing explanation for the shape of the division of innovative labor is known as the "mirroring hypothesis," which states that innovative efforts take place across organizations in a way that is generally isomorphic, or "mirrors," the structure of products that these firms produce (Baldwin 2008). Much of this literature focuses on the activities of large industrial manufacturers and their suppliers as they work to make their complex products less integrated and more modular (Brusoni 2005, Christensen 2006, Argyres and Bigelow 2010). Modular product structures allow firms to specialize and divide product development labor efficiently across multiple organizations and also outsource many design activities to suppliers (Langlois 2003, Christensen 2006). According to the mirroring hypothesis, suppliers responsible for manufacturing components are taking a greater hand in innovating around those components (i.e., "component innovation"), whereas their large industrial customers focus more on innovating at a broader, productwide level that is more concerned with the interactions *between* components (Anderson and Tushman 1990, Baldwin 2008). This productwide innovation is referred to as "architectural innovation" (Henderson and Clark 1990), in that such activity changes elements of the schema through which product components are organized (i.e., product architectures; see Ulrich 1995).

Digital technologies, however, may pose a problem to the mirroring hypothesis. A certain class of digital technologies, known as "digital control systems," is becoming ubiquitous in contemporary complex products, spanning widely different components across those products (Franklin et al. 1998). These digital systems monitor and control components with respect to other indirectly connected components, often acting as the core integrative systems of those complex products (Hobday 1998, p. 695). The transformational potential of digital controls blurs the stabilized boundaries between components in what can be fairly modular product architectures because these digital technologies integrate across previously unconnected product components. Digital control systems are separate from the traditional product structure and integrate, monitor, and control the components that form that structure. This cross-component integration undermines the ability of component interfaces to substitute for coordination and component knowledge and thus leads us to the question of whether the division of innovative labor suggested by the mirroring hypothesis holds in contexts abundant in component-spanning digital control systems. An emerging view, referred to as the "systems integration perspective" (Prencipe et al. 2003), offers an alternative lens for understanding the division of innovative labor when digital controls span complex product architectures.

The systems integration perspective holds that manufacturers of complex products need to integrate and coordinate both internally and externally designed components within a given product architecture, thus maintaining capabilities wider than those needed to support their production (Brusoni et al. 2001; Fine and Whitney 1998; Grandstrand et al. 1997; Prencipe 2000; Takeishi 2001, 2002). Hence, in the wake of a major shift in a product's architecture, systems integrators need to develop internal capabilities in components to gain better understanding of the inner workings of the new components. They cannot rely solely on external suppliers to gain knowledge about new developments (Fine and Whitney 1999, Takeishi 2002). Furthermore, these suppliers should, in turn, gain broader, cross-subsystem expertise to better provide bundled systems to their customers (Davies 2003).

The mirroring hypothesis and the systems integration perspective often present contradictory assumptions about the division of innovative labor after major shifts in product structures. However, both perspectives characterize this product structure in terms of a single product hierarchy—the product hierarchy that Murmann and Frenken (2006) refer to as an "inclusionary hierarchy." In this study, we draw on systems control theory (Mesarovic et al. 1970) to integrate these perspectives by considering digital control systems as a second product hierarchy in complex products. In doing so, we look to the automotive industry—an industry that has been dramatically affected by digital innovation (Yoo 2010), where digital components have grown exponentially in recent decades (King and Lyytinen 2005, Leen and Heffernan 2002, Henfridsson et al. 2009). Emission controls are particularly relevant to this study because they are perhaps the first widespread automotive innovation that would not have been possible without digital technology (Jurgen 1999). Emission control technologies have been explored both in the literature on organizational innovation (Lee and Veloso 2008) and in research into the effects of digital innovation on the automotive industry (King and Lyytinen 2005).

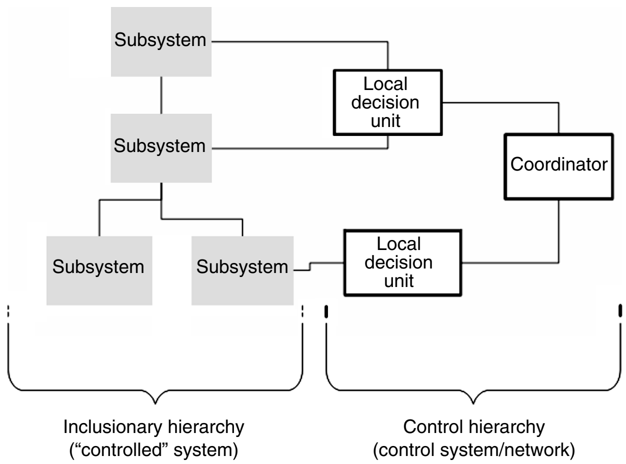
By studying the technological evolution of emission control systems, we look to understand the relationship between technological changes and the resulting division of innovative labor. In particular, we investigate two innovations in emission controls: the first involves technological change in the inclusionary hierarchy (catalyst architecture in 1981) and the second involves change in digital control systems (on-board computing in 1994). Through an analysis of patenting activity between 1970 and 1998, we find that automotive original equipment manufacturers (OEMs) were inclined to increase their relative focus on architectural innovation after a technological shift in the inclusionary product hierarchy—a finding that is consistent with the mirroring hypothesis. However, after the shift in the digital control hierarchy, OEMs refocus on component innovation—a finding consistent with the systems integration perspective. Thus, we find support for the key argument that by distinguishing between two product hierarchies, two distinct theoretical positions (i.e., mirroring hypothesis and systems integration perspective) can be integrated. Furthermore, we offer an explanation for why the emerging systems integration perspective is becoming increasingly relevant, because it helps to explain elements of digital innovation.

The remainder of this paper is organized as follows. We briefly introduce the concept of dual product hierarchies in complex system architectures, followed by our hypotheses on the division of innovative labor in the wake of technological change across each form of hierarchy. Then we present our research and findings. We conclude with a discussion of the implications of this research.

Digital Controls, Control Hierarchies, and Complex Products

Whether systems are biological, mechanical, or social in nature, any given system can be characterized in a variety of hierarchical ordering schemes (Bertalanffy 1968). Although there are multiple hierarchical schemes through which we can make sense of systems, it is customary to focus on a single hierarchy at a time or to take two in opposition. Two ordering schemes commonly held in contrast are structural and functional hierarchies. The former refers to components or parts, whereas the latter describes processes and actions (Bertalanffy 1968). The former emphasizes the physical, whereas the latter emphasizes information. This duality is present in

Figure 1 Illustration of the Dual-Product Hierarchy View of Complex Systems



discussions across the entire range of systems types—from biological systems to linguistic systems. Biological systems contain both hierarchies of particles and hierarchies of genetic code, whereas linguistic systems contain both hierarchies of physiology and hierarchies of syntax (Bertalanffy 1968, Wilson 1969). In each of these examples, the latter, information-related hierarchy, comprises the rules or decision elements associated with the proper function of the system. This second hierarchy controls and coordinates the system, whereas the former describes the parts, components, and subsystems that comprise the system to be controlled and coordinated.

The seminal work on “multilevel control hierarchies” by Mesarovic et al. (1970) applied this dual-hierarchy view to decision making associated with complex sociotechnical systems. Such systems are composed of their functional components, on the one hand, and the multilevel “control hierarchy,” which is often separate from the functional hierarchy of the system itself, on the other (see Figure 1; Mesarovic et al. 1970).[1] Simple decisions can be programmed into controls within each element or module, but complex decisions must span these elements in a form of multilevel control that can include automated controllers and humans. This concept of a multilevel control hierarchy distinguishes between the controlled system hierarchy, which is sometimes referred to as the “inclusionary” hierarchy (e.g., see Murmann and Frenken 2006), and the control hierarchy.

The term “control hierarchy” refers to the organization of decision-making units controlling a system and involves humans, digital controls, analog controls, or some combination thereof (Findeisen et al. 1980). Control units in a multilevel hierarchy are distinguished by goals. *Local decision units* nearer to the component level may address local, operational goals related to specific components and subsystems, whereas *coordinator units* span multiple distributed units and accommodate higher-level goals associated with increasingly broader portions of the system (Mesarovic et al. 1970). Using an automobile as an example, cruise control can be considered a decision unit that is local to the components that produce acceleration, which addresses the goal of keeping the speed within a range, whereas a human driver can be regarded as the coordinator that sets the cruise control in relation to the external environment. In the context of contemporary complex products, we expect to find both a hierarchically decomposed *inclusionary* (“controlled”) hierarchy and a multilevel *control* hierarchy (see Figure 1). The control hierarchy is viewed as a hierarchy (as opposed to a network, for example) because of the subordinate arrangement of the local decision units to the coordinator, and the coordinators to other coordinators, including human coordinators.

Traditionally, organizational theorists did not need to distinguish between inclusionary and control hierarchies because local decision units (whether digital or analog) were generally considered part of the subsystem they control, largely because previous technologies had limited capacity for spanning multiple subsystems. Local controllers are *tightly coupled* with the subsystems that they control and thus fit nicely within any characterization of a complex system in terms of its inclusionary product hierarchy. However, this is changing in recent decades with the emergence of more powerful digital controls. As a result, digital controllers are being increasingly *decoupled* from the subassemblies they control.

Digital controls involve the “control of physical systems with a digital computer or microcontroller” (Franklin et al. 1998, p. 1). Digital controllers offer the ability to span local decision units increasingly without human intervention. With the exponential gains in computing power, microprocessors are capable of handling progressively more complex decisions, and decision logic can be changed even after the controllers are implemented, lending such software-based controls an emergent, unpredictable dimension. As cross-module, digitally integrated controllers become more and more prevalent, microprocessors offer an alternative avenue for fast, accurate, and reliable decision making through programmed software (Findeisen et al. 1980, Drouin et al. 1991). Furthermore, digital controls have a generative aspect to them. Their inclusion in a complex system tends to stimulate additional, often unforeseen, digital applications (Franklin et al. 1998). Thus, digital control systems do not merely replace functionally equivalent inclusionary controls but also dramatically extend the range and scope of automated control, enabling a variety of new applications and thus compounding the uncertainty and unpredictability associated with potential applications. These novel applications, in turn, increase the complexity associated with contemporary products. Tightly coupled, inclusionary controls, in contrast, inevitably work to constrain further innovation of the components that they control at a certain point in the product's evolution (Prencipe 2000). Advanced microprocessors can be programmed to handle more complexity to relax some of these constraints.

In contemporary automobiles, for example, embedded digital control systems now integrate components across increasingly diverse domains (King and Lyytinen 2005). Digital controls do not merely take the place of analog forms of control found within inclusionary automotive subsystems but also enable new possibilities (Koopman 2002, Leen and Hefferman 2002). Through computational (decision-making) performance, accuracy, flexibility, scalability, and networkability (Drouin et al. 1991, Jurgen 1999, Pop et al. 2004), digital controls enable engineers to equip automobiles with the ability to monitor and regulate subsystems in a variety of ways, to process data in real time quickly and reliably, and to link otherwise decoupled subsystems so that these subsystems become responsive to each other (Dorf and Bishop 2008). Through technological advancements in recent decades, digital controls have enabled the control of unprecedented levels of product performance and complexity.

Thus, the fundamental premise of this research is that digital controls are reshaping the way firms organize for complex product innovation. Specifically, as a result of digital innovation, control systems are decoupling from the inclusionary hierarchy (Pop et al. 2004, Steinmueller 2003), and this digital control hierarchy may bring with it the requirements for a new set of integrative capabilities (Curtis et al. 1988, Hobday 1998). To investigate the impact of a view of complex products that considers dual product hierarchies, next we address two competing explanations of the relationship between technological change and the division of innovative labor across a supply chain.

Hypotheses: Technological Change and the Division of Innovative Labor

Organizational research has a history of theorizing about the relationship between technological changes to complex product structures and the activities between firms in a supply chain (Abernathy and Utterback 1978, Anderson and Tushman 1990, Henderson and Clark 1990, Christensen 2006). In this literature, technological changes are typically characterized as either component innovations or architectural innovations (Henderson and Clark 1990, Ulrich 1995), where the former involves changes to technologies within individual components or subsystems and the latter involves changes to schemes for organizing among individual components or subsystems in the context of broader systems (Whitney 1990, Ulrich 1995). Architectures are typically conceived of as either modular or integrated (Ulrich 1995, Sanchez and Mahoney 1996). Modular architectures involve one-to-one mapping between functions and components, which means that components are largely decoupled from each other except through standard and well-defined interfaces (Ulrich 1995). Integrated architectures have a far more complex mapping of functions to components, and their components have multiple connections and interactions (Ulrich 1995).

The firms in a supply chain of a given complex product are also characterized in terms of two broad categories: OEMs and suppliers (Brusoni 2005, Christensen 2006, Argyres and Bigelow 2010). The OEMs are large industrial firms that act as assemblers, integrators, and marketers that bridge customers and the supply chain and generally exercise a great deal of control across the supply chain. Suppliers provide components to OEMS, and, according to much of the literature, OEMs are increasingly relying on suppliers to produce increasingly complex products (Langlois 2003, Argyres and Bigelow 2010). When specialized suppliers merely manufacture components for OEMs, this can be referred to as the interfirm division of labor. When those suppliers engage in the design and innovation around the components that they produce, this can be characterized as the interfirm division of *innovative* labor (Arora and Gambardella 1994), where a more broadly held set of capabilities and knowledge specializations apply. There are a variety of explanations for the relationship between complex product architectures and the distribution of innovative activity across OEMs and suppliers (Brusoni 2005, Christensen 2006).

These explanations can be categorized in terms of two broad perspectives about the relationship between changes to technological architecture, what we refer to as "technological shifts," and the interfirm division of innovative labor. Both of these explanations attend to issues associated with the knowledge resources necessary to innovate with respect to either components or architectures in complex product development. The first explanation is the mirroring hypothesis (Baldwin 2008), which finds its roots in Simon's (1996) concept of nearly decomposable systems and modularity, and in the strategic theories of a firm (i.e., transaction cost economics and resource-based view). Consistent with this view, the relation between changing product architectures and the division of innovative labor is captured in the notion of a dominant design (Anderson and Tushman 1990). The second explanation is the systems integration perspective (Prencipe et al. 2003), rooted in the knowledge-based view of the firm (Kogut and Zander 1992), which indicates that complex product manufacturers need to maintain competencies beyond their immediate needs to innovate effectively.

In the previous section, we distinguished between inclusionary and digital control hierarchies. Although both product hierarchies comprise increasingly modular architectures, the effect of the digital control hierarchy is that of integration across the inclusionary hierarchy.

Based on this distinction, we expect the dynamics associated with changes to inclusionary hierarchies to remain consistent with the mirroring hypothesis and changes to digital control hierarchies to be more consistent with the systems integration perspective. Next, we detail this logic and present our hypotheses.

Inclusionary Hierarchies and the Mirroring Hypothesis

According to the mirroring hypothesis, periods of dramatic technological change often lead to the emergence of a dominant design, after which the competitive dynamics in an industry become more focused on incremental innovation (Abernathy and Utterback 1978, Anderson and Tushman 1990). A dominant design implies a moment of stability in the evolution of a product's architecture, indicating an agreement among various technical, political, and social forces (Anderson and Tushman 1990). This point of agreement is followed by a period of autonomous technological progress, where limited communities of specialists focus on incremental enhancement within the components associated with the dominant design (Tushman and Murmann 1998).

Whether focusing on the architecture of the entire complex products or on particular subsystems, the literature on dominant design finds its roots in the observation that patterns of technological innovation associated with a complex system design are mirrored by the relevant structures within and across organizations in an industry (Abernathy and Utterback 1978). Thus, organizations responsible for higher levels of product hierarchy, such as OEMs, are more directly involved in component-level innovation before a dominant design is established, but they leave component innovation more to their suppliers after the dominant design emerges and clear performance metrics and product interfaces are established (Murmann and Frenken 2006). Similarly, competing suppliers engage in architectural-level innovation before a dominant design emerges in the hopes of influencing the architecture in their favor. However, this diminishes after a standard architecture is established. This situation results in relative stability and incremental change until the next technological shift to a subsequent dominant design (Anderson and Tushman 1990).

When a dominant design emerges for a system or subsystem, the focus of overall innovation shifts to incremental component innovation (Henderson and Clark 1990, Ulrich 1995). Such a technological shift reduces market uncertainty and allows assemblers to incorporate key suppliers into their product development activities strategically (Venkatesan 1992, Anderson and Tushman 1990), thus stimulating the rise of specialized suppliers that contribute to subsequent product innovations. These suppliers take on a larger share in product development and obtain valuable, focused experience that dramatically increases their knowledge about the component or subassembly. Because of this specialized knowledge, they offer their customers advantages in quality, cost, and time to market the components and subassemblies they design and produce (Clark 1989, Clark and Fujimoto 1991, Ragatz et al. 1997, Handfield et al. 1999). The use of trusted suppliers reduces an OEM's need to maintain knowledge in every component or subassembly, allowing them to focus more on architectural and systemwide innovation. Thus, after a technological shift in a given complex product architecture, according to the mirroring hypothesis, there is a decreased share in overall component-level innovation on the part of the assembling manufacturers (Henderson and Clark 1990, Murmann and Frenken 2006). Furthermore, there is less need for suppliers to attend to architectural issues because the architecture is settled, and the interfaces are clearly defined and become standard. However, even in the context of highly modular product architectures, OEMs will not relinquish component innovation entirely, particularly with respect to strategically important components. The knowledge of key components remains important to an organization's ability to innovate on the product's architecture and to coordinate product development across the supply chain (Sanchez and Mahoney 1996, Christensen 2006). Therefore, finding situations wherein OEMs completely abandon component innovation, for example, is unlikely. What can be found instead is the decrease in relative proportion or overall share in the ever-changing level of component innovation compared with the share of the suppliers.

As technological change in the inclusionary hierarchy of complex products is relatively modular and represents the nested components, subsystems, and systems most often characterized in organizational literature, we expect changes in the inclusionary hierarchy to reflect the assumptions of the mirroring hypothesis. Therefore, we hypothesize the following.

Hypothesis 1A (H1A). *After a technological shift in the inclusionary product hierarchy of a complex product, the suppliers' overall share in component innovation increases.*

Hypothesis 1B (H1B). *After a technological shift in the inclusionary product hierarchy of a complex product, the OEMs' overall share in architectural innovation increases.*

Digital Control Hierarchies and the Systems Integration Perspective

The systems integration perspective (Prencipe et al. 2003) can be used in contrast to the mirroring hypothesis. According to the systems integration perspective, as a system evolves, the product gains complexity with a greater number of interfaces and linkages (Murmann and Frenken 2006, Tushman and Murmann 1998). It is up to the systems integrators (i.e., "OEMs") to build the requisite knowledge for managing these systems and innovating across both components and systems. OEMs, as systems integrators, are firms that possess technological and organizational capabilities to integrate changes and improvements in internally and externally designed and produced inputs within existing product architectures (Brusoni et al. 2001, p. 614). A stream of research associated with this view provides empirical evidence that OEMs possess product design knowledge and related capabilities for a much broader set of components than those they directly design and manufacture (Brusoni et al. 2001; Fine and Whitney 1999; Grandstrand et al. 1997; Prencipe 2000; Takeishi 2001, 2002). OEMs function as all-round knowledgeable firms, capable of coordinating changes in a variety of relevant technical fields (Brusoni et al. 2001, Prencipe 2002). They also maintain the capabilities required for introducing new product subarchitectures. OEMs must not only maintain component knowledge and architectural integration knowledge but also organizational knowledge on how to integrate different specialist suppliers in the supply chain (Christensen 2006).

When a major technological shift occurs at a subsystem level, OEMs need to develop internal capabilities in components to gain better understanding of the inner workings of the new subarchitecture and components. OEMs cannot rely solely on external component suppliers to adequately stay current about new developments (Fine and Whitney 1999, Takeishi 2002). Critical engineering knowledge may leak to potential competitors, and OEMs may lose negotiating power to suppliers if they rely too heavily on suppliers for new knowledge (Fine and Whitney 1999, Takeishi 2002). Consequently, as a given system evolves with increasing complexity, OEMs need to gain better understanding of the component functionality to assess, test, and integrate components produced from both in-house research and development (R&D) functions and external suppliers (Prencipe 2000). According to the systems integration perspective, after a technological shift, suppliers also look to gain architectural expertise to move downstream in the supply chain and potentially improve their market position by providing aggregated, or "bundled," subsystems (Davies 2003, Dosi et al. 2003).

As indicated above, innovations associated with digital control hierarchies represent a relatively different form of innovation for firms that manufacture complex electromechanical products. Digital control systems can be decoupled from traditional inclusionary product hierarchies (Findeisen et al. 1980, Drouin et al. 1991, Steinmueller 2003, Pop et al. 2004), integrate across these hierarchies (Hobday 1998), and allow for ever-greater integrative combinations in the future (Franklin et al. 1998). Digital controls are necessary for breaching the ceiling of limited intermodule coordination associated with inclusionary product hierarchies (Prencipe 2000). Moreover, the practices, competencies, and forms of knowledge associated with digital systems development are fundamentally different from the design of other artifacts (Turner 1987, Kettunen and Laanti 2005). The process of design for digital systems is different from that for electromechanical products in both the steps of the process and in the way tools are used in the design activity (Whitney 1990). In addition, digital system developers necessarily bring capabilities outside the application domain that they must span and integrate with the application domain (Curtis et al. 1988).

Thus, as digital control systems become more prevalent, controls of inclusionary product hierarchies become decoupled from those hierarchies, and the systems integration perspective would indicate that there should then be a shift toward innovative practices that reflect this spanning or integrating of the inclusionary product hierarchy (Prencipe 2000, Brusoni et al. 2001). Therefore, we hypothesize that technological shifts in the digital control hierarchy are likely to require OEMs to expand their relative share of component innovations, whereas their suppliers would become increasingly involved in architectural innovation. Thus, we expect technological shifts in the digital control hierarchy to be consistent with the systems integration perspective.

Hypothesis 2A (H2A). *After a technological shift in the digital control hierarchy, the suppliers' overall share in architectural innovation increases.*

Hypothesis 2B (H2B). *After a technological shift in the digital control hierarchy, the OEMs' overall share in component innovation increases.*

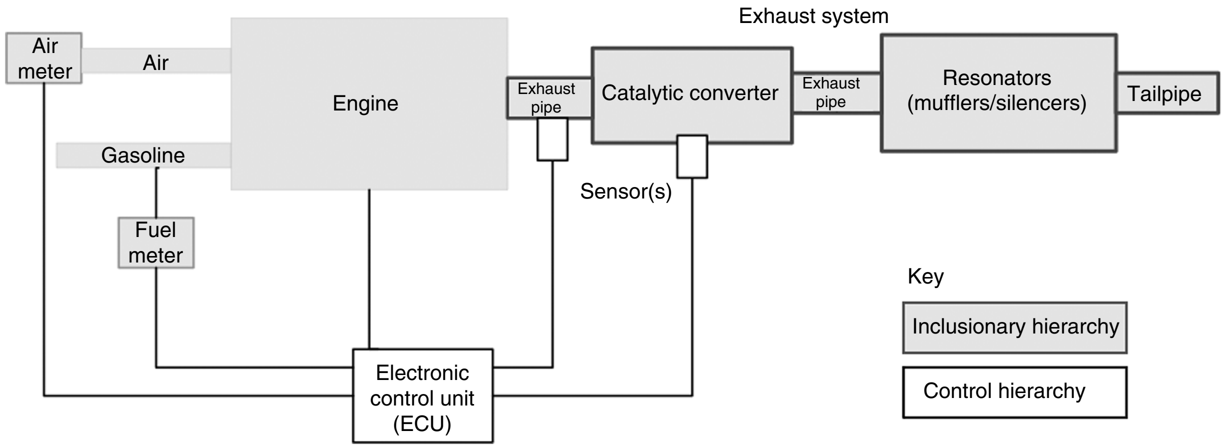
To test these hypotheses across technological shifts involving both the inclusionary and the digital control hierarchies, we study the patterns of organizational innovation associated with nearly two decades of automotive emissions control systems.

Research

Research Context: Automotive Emissions Control

Automobile emissions control technology, between 1970 and 1998, provides a suitable context for exploring complex technological shifts involving both the inclusionary and the digital control hierarchies for three reasons. First, emissions control systems are the first automotive subsystems where the control functionality demanded by environmental forces (i.e., regulation) is not met with existing technologies, necessitating digital control (Jurgen 1999). Second, the architecture, with respect to the inclusionary product hierarchy, after intense competition across a variety of architectures in the 1970s, remains completely stable since the dominant design emerged in 1981. Third, largely because of environmental concerns, digital control hierarchies related to

Figure 2 Digital Control and Inclusionary Hierarchies in Emissions Control Systems

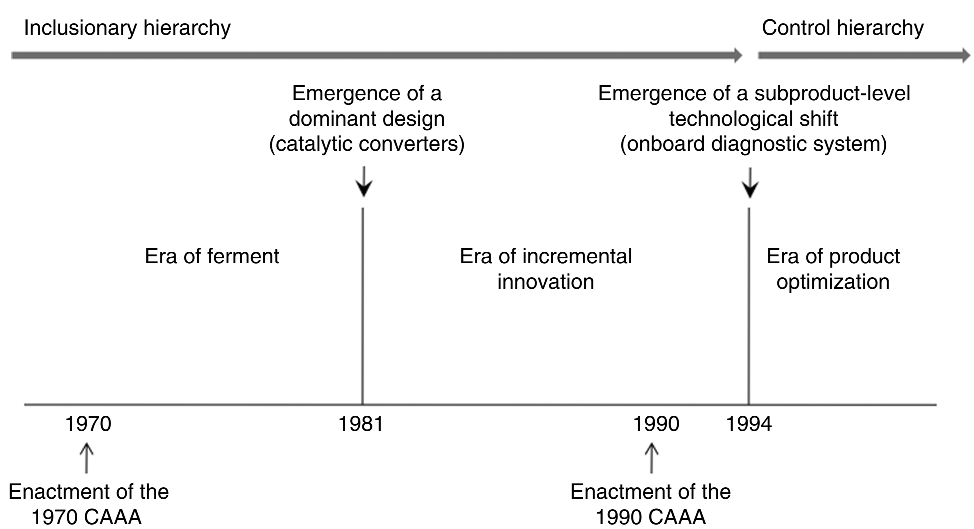


emissions control are under increased pressure for more complex controls in response to regulation and consumer tastes (Powers and Nicastri 2000, Papodopoulos and Grante 2005). Emissions control systems underwent two readily identifiable technological shifts over the course of two decades. The first involved a dominant design in the inclusionary product hierarchy, and the second involved a technological shift of the digital control hierarchy that integrated across these systems over a decade later (see Figure 2).

In the development of automobile emissions control systems, a dominant product-level design in the inclusionary product hierarchy emerged in 1981: an architecture described as a "catalyst-based three-way catalytic converter" (TWC). This technological shift was followed by a period of incremental change until 1994 with the advanced onboard diagnostic electronic control module (OBD), a technological shift in the digital control hierarchy. The subsystem-level technological evolution in automobile emissions control technologies from 1970 to 1998 is shown in Figure 3. Next, we describe each of these architectural innovations.

Technological Shift in the Inclusionary Product Hierarchy. Catalyst technology was the primary focus of innovation in automobile emissions control systems throughout the 1970s. High automobile tailpipe emissions reduction requirements mandated by the Clean Air Act Amendments in 1970 (1970 CAAA) led to the development of catalyst-based emissions reduction technology, or what is commonly referred to as catalytic converter technology. The regulation required automakers to reduce three pollutants simultaneously, namely, hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NO, NO_2; referred to as NO_x). Potential solutions to emissions control problems abounded in the 1970s. An architecture involving "add-in-type" catalytic converters emerged as the viable, standard technical solution for reducing all three pollutants. Eventually, the TWC converter technology using monolithic-type

Figure 3 Technology Evolution of the Automobile Emissions Control Technology



catalysts became the dominant design for automobile emissions control systems in 1981 and finally satisfied the 90% reduction requirement originally mandated in the Amendments of the Clean Air Act in 1970.

Technological Shift in the Digital Control Hierarchy. Many subsequent innovative efforts following the TWC standard in 1981 focused on making incremental improvements in the inclusionary product hierarchy, on components such as catalysts and fuel injection systems. Accompanying these incremental innovations, however, was a growing focus on developing electronics subsystems. Much of this focus on electronics was due to pressure from the U.S. Environmental Protection Agency (EPA), which was looking to impose more stringent automobile emissions reduction requirements (Lee and Veloso 2008). Amendments to the Clean Air Act in 1990 (1990 CAAA) mandated short-term lowering of both HC and NO_x by 39% and longer-term lowering of HC by 70%, CO by 50%, and NO_x by 80% relative to the 1990 emissions reduction levels (Mondt 2000). These pressures eventually resulted in the commercialization of the advanced electronic onboard diagnostic module (OMD). OMD's main functions were to monitor all emissions-related devices mounted on a vehicle, which included not only hydrogen reduction devices during the cold-start but also catalyst efficiency, engine misfire, oxygen sensor response, abnormality in fuel supply system, exhaust gas recirculation (EGR) valve, secondary air system, and abnormal engine sensor output (Mondt 2000).

Research Approach

We used these two technological shifts to gain insight into the subsequent division of innovative labor and thereby determine whether the evidence supports our two sets of hypotheses (H1A/H1B, inclusionary shift consistent with mirroring; and H2A/H2B, digital control shift consistent with systems integration). To do this, we looked at all the patents associated with automobile emissions control systems to see whether (1) the source of innovation was the OEM or a supplier, and whether (2) the specific type of change was component or architectural. In analyzing the data, we used logistic regression analysis to isolate the effects of the technological change on the overall division of innovative labor between automotive OEMs and suppliers. Both groups continually engage in both forms of innovation (component and architectural). Therefore, we endeavored to measure the effect of the *overall proclivity* for these groups to engage in different forms of innovation in the wake of a technology shift. Much of the data were drawn from an in-depth patent search. In the following, we describe this patent search and the measures used in the analysis.

Patent Search. As the first step in the analysis, the first author identified relevant patents in the auto emissions control technology using successfully applied patents in the U.S. Patent and Trademark Office (USPTO) public database from 1970 to 1998. He used two approaches in building a patent database on automobile emissions control systems, namely, the class-based search and the abstract-based keyword search. The goal of using both search strategies is to capture relevant patents comprehensively. The class-based search and the abstract-based keyword search complement each other. The class-based search, with its detailed subclasses, helps researchers capture a broad range of relevant patents that may not otherwise be captured alone under the abstract-based keyword search. However, when the set of relevant technologies is diverse, the class-based search approach could miss relevant patents within its identified classes. The abstract-based keyword search complements the class-based approach by allowing researchers to double-check findings and identify potentially important patents not found under class-based search.

In the class-based search approach, we adopted the patent classes for the catalytic converter technology previously used by the Battelle research group (Campbell and Levine 1984). Battelle research used patent subclasses within two patent classes, namely, Class 55 (gas separation) and Class 423 (inorganic chemistry). Class 55 represents the internal structure and control systems used for catalytic converters, whereas Class 423 is mostly related to the chemical composition of a catalyst or its supporting materials (Campbell and Levine 1984). In the abstract-based keyword search, we used different combinations of seven keywords, namely, "catalytic converter," "emission," "automobile," "catalyst," "pollution," "exhaust," and "engine," to obtain an automobile emissions control patent set. Two searched patent sets from both methods were then combined, and duplicate patents were eliminated. The abstract-based keyword search was helpful in identifying potentially relevant patents not captured under the class-based search method. Moreover, we screened out irrelevant patents by carefully reading abstracts of searched patents. Our purpose is to generate a cleaner patent set by identifying the patents that belong to the search criteria but are not necessarily related to the technology of interest. For example, a patent for catalyst pollution control technology specifically designed for an electric power plant could belong to the same patent class as other catalyst patents granted for automobile applications. After screening the searched patents, we generated a time-series patent data set on automobile emissions control technologies from 1970 to 1998. We focused our search on 237 firms that received 2,100 patents, accounting for approximately 93% of the overall patenting activities associated with automotive emission controls from 1970 to 1998. Next we describe the variables used in our analysis.

Dependent and Explanatory Variables

Innovation. We used the firms' successful U.S. patent applications in automobile emissions control technology as a measure of innovation activities. The use of patents has various limitations (Acs et al. 2002, Archibugi and Pianta 1996, Basberg 1987, Griliches 1990, Lanjouw et al. 1998, Popp 2005, Scherer 1983). Not all inventions are patented, and the proportion and quality of inventions patented may vary depending on the sector and the period being investigated (e.g., Basberg 1987, Lanjouw et al. 1998, Popp 2005). In some instances, firms apply for patents only to prevent other firms from "inventing around" a patented invention or exploiting the patents (Cohen 1995, Pavitt 1985). Moreover, high variances and skewing exist in the distribution of patent values (Griliches 1990, Lanjouw et al. 1998, Scherer and Harhoff 2000). The propensity to patent also varies across industries and countries (Basberg 1987, Cohen et al. 2000, Pavitt 1985). However, with these limitations in mind, there exists a substantial amount of precedent for using patents as an operationalizable proxy for innovation (e.g., Griliches 1990, Lanjouw et al. 1998, Popp 2003). Patent statistics represents a "unique resource for the analysis of the process of technical change," providing an abundant data with potential industrial, organizational, and technical details (Griliches 1990, Lanjouw et al. 1998). Pavitt (1985) also claimed that studies on patents can provide detailed and consistent information of how firms solve technological problems especially when patent statistics are combined with qualitative knowledge of technology.

Innovation Type. We developed a category for innovation to distinguish its types, namely, architectural and component. We coded the patents using the generic definitions of component and architectural innovation provided by Henderson and Clark (1990; see also Ulrich 1995). The patents that capture the identifiable physical part of the product represent component innovation, whereas those that address the interfacial problems among components and how the components can be linked together into a whole system were coded as architectural innovation.[2] Table 1 shows the key features of the patent categorization and relevant patent classes for automobile subsystems.

Inclusionary and Digital Control Product Hierarchies. To capture the effect of a technological shift in the inclusionary product hierarchy (catalytic converter in 1981) as well as in digital control technology (electronic onboard diagnostic module in 1994) on automakers' propensity for architectural (or component) innovation, we defined two periods: the inclusionary hierarchy dominant design period (1981–1993) and the digital control hierarchy technology-shift period (1994–1998). Because innovation in auto emissions control regulation was driven by a government regulation enacted in 1970 (i.e., the Clean Air Act of 1970), we defined the inclusionary hierarchy dominant design era as the period that captures the

Table 1 Automotive Emission Control Subsystems (AECS) and Relevant Patent Classes

AECS subsystem[a]	Classes	Example technologies	Innovation-type category
Catalyst	422/171	Porous catalyst carrier, catalyst support materials, Palladium TWC catalyst	Component
	422/177	Catalyst support design, absorber system, catalyst support materials	Component
	422/213.2	Catalyst materials, wash-coat materials	Component
Electronics	60/274	Air-to-fuel ratio control, determining efficiency of catalytic converter, electronic heating control	Architectural
	60/276	Air-to-fuel ratio control, determining efficiency of catalytic converter	Architectural
	60/277	Determining efficiency of catalytic converter	Architectural
	60/278	EGR control, spark timing control, absorber system	Architectural
	337/382	Temperature sensor	Component
Manufacturing	29/890	Assembly method for catalytic converter, catalytic converter housing design, manufacturing process	Architectural
	422/179	Catalytic converter housing design, mounting materials design	Architectural
	422/176	Catalyst support design, catalyst converter housing design	Architectural
	425/461	Extrusion die for substrates	Component
	422/174	Heated cellular substrates	Component

[a]We further disaggregated the automobile emission control technology patents into three subsystem technology categories: catalyst, electronics, and manufacturing technologies to help the reader understand better how the three subsystem technologies comprising the automobile emission control technology are related to the innovation categories.

date of the enactment of the technology-forcing auto emissions control government regulation (i.e., the Clean Air Act of 1970) until the emergence of the digital control technology in 1994 (1970–1993). We name the period following the emergence of the digital control technology as the digital control hierarchy technology shift era (1994–1998). We then generated interaction terms between these two dominant design periods with the automaker dummy to examine whether automakers' propensity for different types of innovation (i.e., architectural and component) is related to the two different technological shifts (i.e., inclusionary or control hierarchy).

To verify 1981 as the point of stabilization in the inclusionary hierarchy of emission control systems, we examined the degree to which the technology was self-contained at that point. According to Campbell and Levine (1994), as the technology is being developed, the degree to which the technology is self-contained—that is, the proportion of patent citations given to prior technology from its own technology domain—increases until the technology becomes commercialized. The timing of an emergence of a dominant design is closely related to the commercialization of a new technology (Anderson and Tushman 1990). Therefore, what Campbell and Levine's (1994) study implies is that the timing at which the technology self-containment approaches its maximum value captures the emergence of the dominant design. We estimated and plotted technology self-containment over time and found that the technology self-containment measure increased until 1980 and then leveled off (see Figure 4). This finding strongly supports the use of 1981 as the first year of the "era" following the establishment of a dominant design. When a dominant design emerged in auto emissions control technology—that is, a catalytic converter based on three-way catalysts—nearly 70 % of new vehicles were equipped with this device in 1981 (Gerard and Lave 2005).

Figure 4 **Technology Self-Containment from 1970 to 1998**

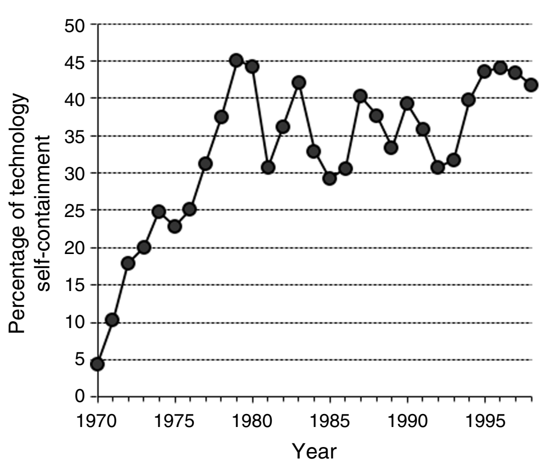
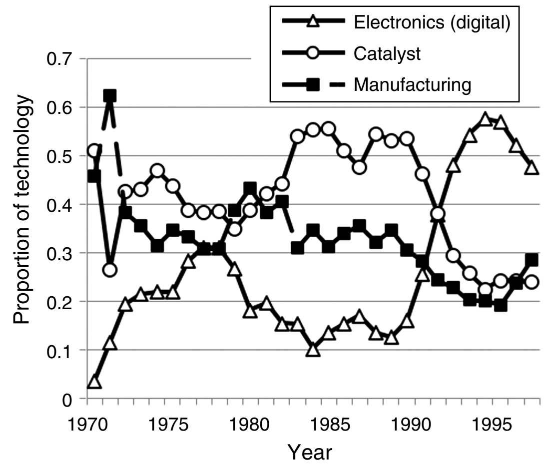


Figure 5 **Proportion of Digital Electronics and Nondigital Technology**



Furthermore, we looked to empirically verify the 1994 start to the second era, following the architectural innovation in the digital control hierarchy. We examined how the proportion of digital electronics technologies compared with that of nondigital technologies (i.e., catalyst and manufacturing) over time (see Figure 5). As expected, we found that the proportion of digital electronics technology becomes higher than that of nondigital technologies starting in 1993. Prior to 1993, the proportion of digital electronics technology remained lower than that of nondigital technologies. Again, we marked the beginning of the "era" following the architectural innovation in the digital control hierarchy in 1994.

Control Variables

Regulatory Compliance Expenditure. We used the cost estimates for automobile emission control devices to control for the effect of regulatory pressures on the development of automobile emission control technologies. We applied a one-year lag structure to the regulatory compliance expenditure variable (Jaffe and Palmer 1997). We used a number of different sources, such as the EPA (1990) and the California Air Resource Board reports, to compile the cost data for emission control devices (CARB 1996). The EPA's (1990) cost estimate provides aggregated capital cost estimates for emissions control devices, including evaporative emissions canisters, high-altitude emissions control, catalytic converters, exhaust gas recirculation units, and air pump units (EPA 1990, McConnell et al. 1995).

Auto Sales. We included the U.S. retail automobile sales to control for the potential market force in the development of emission control devices. Ward's publication on motor vehicle facts and figures was our source for the U.S. automobile retail sales data.

Automotive Patents. We included total patent counts in automotive technology to control for the potential impact of innovation trend in the automobile industry on innovation in automobile emission control technologies. To obtain the overall patent counts in automotive technology, we used the U.S. Patent Classification (USPC), selected subclasses listed under "Automobile" in the USPC index and Class 180 (Motor Vehicles), and counted patents applied under these subclasses from 1970 to 1998.

Technology Self-Containment. We control for the dependency of automobile emission control technology on other fields. According to Campbell and Levine (1994), the proportion of citations given to other technical fields decreases as the technology evolves until the timing of commercialization. We calculated the changes in the degree of technology self-containment over time by examining the percentage of citations given to previously granted patents in the automobile emission control technology.

Total Patents. We included a general economy-wide patenting activity trend variable using the applied total patent counts using the USPTO database from 1970 to 1998.

Technology Choice. We control for the functional attributes of the three main subsystems of automotive control technology (see Table 1), namely, catalyst, electronics, and manufacturing. The innovation-type variable (component and architectural innovation) captures the physical attributes of technology, whereas this technology-choice variable captures the technology's functional attributes. Thus, the innovation-type variable is not confounded by the technology-choice variable.

Data Analysis
To analyze the relative propensity for OEMs to engage in architectural and component innovation following a technological shift, we fitted logistic regressions where the *innovation-type* variable (i.e., component and architectural innovation were coded as 1 and 0, respectively) was used as a dependent variable. Because there are multiple observations for each firm, observations within firms may not be independent. To address this potential problem, we reported the results with robust standard errors using the Huber–White estimator for variance. This methodological approach relaxes the assumption that observations within firms are independent (White 1980). We also performed firm fixed-effect logit regressions to build more robustness into our analysis.[3] The advantage of adopting firm fixed effects is that they control for firm-associated unobservable heterogeneities arising from firms' potential differences in strategies and capabilities (Penner-Hahn and Shaver 2005), as well as the different propensities for patenting (Pavitt 1985). In the fixed-effects analysis, we focused on the top 10 patenting firms, including five automakers, namely, General Motors, Toyota, Ford, Nissan, and Honda; and five suppliers, namely, Engelhard, Corning, Nippondenso, EMITEC, and NGK Insulator. We selected the top 10 patenting firms for the fixed-effect regressions because firms' patenting activity is skewed. For example, among the 237 firms that patented, these top 10 patenting firms accounted for about 51% of the total patenting activities (1,065 patents),[4] and about 54% of firms (130 firms) had fewer than 10 patents over the 30-year period. Thus, we reduced the risk of obtaining inconsistent fixed-effects estimates by using the top representative patenting firms' data (Katila and Chen 2008).[5] We ran logistic regressions for each of the two distinct time periods and compared the results. For architectural innovation in the inclusionary hierarchy, we used the time frame between 1970 and 1993. In the digital control hierarchy analysis, we used the period from 1981 to 1998.

Results
Table 2 presents the descriptive statistics and correlation matrix for the variables used for the analysis, indicating that some variables are highly correlated. High correlations among variables cause significant muliticollinearity and may bias the regression estimates (Kennedy 1985). This study approaches these roblems of mulitricollinearity by comparing the nested regression models. This approach has been found to be useful in other research on ecological dynamics (Baum et al. 1995, Tucker et al. 1990).[6, 7]

Table 3 reports the results of eight logistic regressions on the component innovation. Models 1–6 present the results of the pooled logistic regressions, and models 7 and 8 show the results of the firm fixed-effects logistic regression. Models 1 and 2 add the main effect "technological shift" variables—that is, the inclusionary hierarchy (β_1) and the digital control (β_2)—to the control variables, respectively. Model 1 indicates that the coefficient for the inclusionary hierarchy variable is positive (β_1, 0.44) but insignificant. In contrast, model 2 indicates that the coefficient for the digital control variable is negative and significant (β_2, −1.55). These findings weakly indicate that different levels of technological shifts have differing effects on firms' overall propensity for component innovation. The technology shift in the inclusionary hierarchy increases the likelihood of the overall component innovation, whereas the technology shift in the digital control hierarchy decreases the likelihood of component innovation. As such, this may increase the likelihood of architectural innovation. Component innovation is emphasized more following the technology shift in the inclusionary hierarchy, as shown by a positive coefficient in model 1 (β_1). The negative

Table 2 Descriptive Statistics and Correlations

Variables	Mean	SD	1	2	3	4	5	6	7	8	9	10	11
1. *Inclusionary hierarchy dummy* (1981–1993)	0.34	0.47											
2. *Digital control hierarchy dummy* (1994–1998)	0.40	0.49	−0.57*										
3. *Innovation type*[a]	0.58	0.49	0.16*	−0.05*									
4. *Automaker dummy*	0.45	0.50	−0.02	0.07*	−0.24*								
5. *Catalyst technology*	0.33	0.47	0.08*	−0.16*	0.58*	−0.16*							
6. *Electronics technology*	0.38	0.49	−0.06*	0.22*	−0.54*	0.23*	−0.56*						
7. *Manufacturing technology*	0.28	0.45	−0.02	−0.07*	−0.03	−0.08*	−0.45*	−0.50*					
8. *Regulatory compliance expenditure*[b]	648.57	268.70	0.24*	0.59*	0.08*	0.10*	−0.12*	0.20*	−0.09*				
9. *Auto sales* (10^6)	6.76	1.20	−0.34*	−0.40*	−0.06*	−0.07*	0.12*	−0.17*	0.05*	−0.74*			
10. *Patenting in automotive technology* (10^3)	1.21	0.35	−0.21*	0.87*	0.02	0.07*	−0.15*	0.21*	−0.07*	0.75*	−0.60*		
11. *Technology self-containment*	0.35	0.09	−0.06*	0.66*	0.06*	0.11*	−0.11*	0.16*	−0.06*	0.84*	−0.53*	0.72*	
12. *Total patenting* (10^6)	0.17	0.05	−0.12*	0.82*	0.00	0.08*	−0.18*	0.25*	−0.08*	0.80*	−0.73*	0.96*	0.71*

Note. $n = 2{,}100$.
[a]Component innovation = 1 and architectural innovation = 0.
[b]Per vehicle (US$).
$^*p < 0.05$.

Table 3 Results of the Logistic Regression on Component Innovation, 1970–1998

	Pooled						Fixed effects	
Variables	Model 1 1970–1993	Model 2 1981–1998	Model 3 1970–1993	Model 4 1981–1998	Model 5 1970–1993	Model 6 1981–1998	Model 7 1970–1993	Model 8 1981–1998
β_1 *Inclusionary hierarchy* (1981–1993)	0.44 (0.59)		1.12† (0.65)		1.94** (0.57)		4.12* (1.78)	
β_2 *Digital control hierarchy* (1994–1998)		−1.55** (0.54)		−1.86** (0.57)		−1.80** (0.57)		−0.83 (0.90)
β_3 *Inclusionary hierarchy × Automaker dummy*			−1.31** (0.39)		−1.28** (0.39)		−2.69† (1.55)	
β_4 *Digital control hierarchy × Automaker dummy*				0.88** (0.29)		0.88** (0.29)		0.06 (0.51)
β_5 *Automaker dummy*			−0.14 (0.31)	−1.42*** (0.23)	−0.15 (0.32)	−1.43*** (0.23)		
β_6 *Catalyst technology*	5.00*** (0.42)	2.56*** (0.33)	4.98*** (0.43)	2.59*** (0.33)	5.00*** (0.43)	2.60*** (0.33)	4.07*** (0.52)	2.77*** (0.44)
β_7 *Electronics technology*	−2.09*** (0.21)	−2.23*** (0.15)	−1.97*** (0.22)	−2.13*** (0.16)	−1.97*** (0.23)	−2.11*** (0.15)	−1.88*** (0.31)	−1.89*** (0.23)
β_8 *Regulatory compliance expenditure* ($1/10^3$)	1.13 (1.01)	12.61* (5.39)	1.14 (1.03)	10.57† (5.53)	0.53 (1.06)	7.57 (6.46)	−2.11 (1.67)	3.61 (7.43)
β_9 *Auto sales* ($1/10^6$)	−0.09 (0.11)	−0.01 (0.16)	−0.08 (0.11)	0.03 (0.17)	0.05 (0.12)	0.12 (0.25)	0.40† (0.19)	0.29 (0.24)
β_{10} *Automotive patents* ($1/10^3$)	2.91** (0.89)	−0.56 (0.69)	2.81** (0.92)	−0.35 (0.71)			3.64*** (0.96)	1.40† (0.85)
β_{11} *Technology self-containment*	3.30† (1.79)	3.58 (3.20)	3.27† (1.83)	2.96 (3.34)	4.09* (1.87)	2.72 (3.34)	6.21 (3.50)	−2.19 (4.90)
β_{12} *Total patents* ($1/10^6$)					1.01† (5.48)	1.60 (6.40)		
β_o *Intercept*	−3.96*** (1.14)	−8.54* (3.60)	−3.89** (1.18)	−6.66* (3.70)	−3.92** (1.41)	−5.58† (3.44)		
N	1,269	1,538	1,269	1,538	1,269	1,538	634	834
Log-likelihood	−402.34	−649.40	−381.29	−624.14	−384.40	−624.23	−180.01	−297.19
Model χ^2	904.55***	760.21***	946.65***	810.73***	940.43***	810.54***	333.59***	303.90***

Notes. Dependent variable: *Innovation type* (component innovation). Robust standard errors are in parentheses.
$^{\dagger}p < 0.1$; $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

coefficient for the technological shift in the digital control hierarchy in model 2 (β_2) denotes the firms' overall propensity for architectural innovation decreased.

The catalyst and electronics technology regression coefficients (i.e., β_6 and β_7) are positive and negative, respectively, in all models (models 1–7). These regression findings largely capture the component nature of the catalyst and architectural nature of the electronics emission control technologies. The coefficient for U.S. retail automobile sales (β_9) suggests that automobile sales did not have significant influence on firms' propensities for either component or architectural innovation. Moreover, regulatory compliance expenditure (β_8) is only weakly related to firms' propensity for component (or architectural) innovation because its impact is found to be weakly significant only during the period of 1981–1998. The regression coefficient for the overall patenting trend in the automotive technology (β_{10}, Model 1) is positive and significant during the period of 1970–1993.[8] The firms' propensity for component innovation in automobile emissions control technology is significantly related to the overall patenting trends in the automotive technology until the early 1990s. The regression coefficient for the technology self-containment variable was found to be positive and significant during 1970–1993 but not during 1981–1998 (models 1–6). This implies that the firms' R&D decisions on the development of technology during the period of 1970–1993 were related to the rapidly established body of developing knowledge about automotive emissions control.

In models 3 and 4, we added the interaction of the dominant design and the automaker dummy (β_5) to models 1 (β_3) and 2 (β_4), respectively. Regression coefficients for the automaker dummy are negative, which indicates that automakers are mainly involved in architectural innovation rather than component innovation. Moreover, the dominant design coefficients for both the inclusionary hierarchy (β_1) and digital control hierarchy (β_2) in models 3 and 4 measure the effect of the inclusionary and the digital control hierarchy architectural innovations for the base (suppliers) rather than the effect of different levels of architectural innovation on the overall component innovation. Thus, the positive coefficient for inclusionary hierarchy dominant design dummies (β_1, 1.12) in model 3 indicates that the architectural innovation in the inclusionary hierarchy increased the probability for suppliers' involvement in component innovation. The negative coefficient for the shift in the digital control hierarchy (β_2, -1.86) in model 4 suggests that suppliers paid relatively more attention to architectural innovation after the technological shift in the digital control hierarchy. The division of innovative labor in the 1980s and 1990s indicates that suppliers focused increasingly on component innovation following the technological shift in the inclusionary product hierarchy and then focused relatively more on architectural innovation following the shift of the digital control hierarchy, as shown by coefficients β_1 and β_2 in models 1 and 2, respectively.

The interaction between the inclusionary hierarchy variable and the automaker dummy (β_3) in model 3 represents the differential effect of the technological shift on automakers' innovation in relation to that of the suppliers rather than the effect solely on automakers' innovation[9] (Yip and Tsang 2007). Similarly, the interaction term between the technological shift of the control hierarchy and the automaker dummy (β_4) in model 4 represents a differential effect of the shift in the digital control hierarchy on automakers' innovation over that of the suppliers rather than the sole effect of the technology shift of the digital control hierarchy on automakers' innovation. Thus, the effect of the inclusionary dominant design on automakers' component innovation is -0.09 rather than -1.31. With the component innovation as the dependent variable, the negative coefficient for the interaction term (-0.09) suggests that automakers had higher propensity for architectural innovation following a technological shift in the inclusionary hierarchy. Similarly, the effect of the shift in the digital control hierarchy on automakers' component innovation is -0.98 rather than 0.88, implying that automakers also focused more on architectural innovation following the emergence of a digital control hierarchy in auto electronics in 1994. However, because of the nonlinear nature of the logit model, interpreting the interaction effect by simply relying on the significance and signs of the logic coefficients could be misleading (Bowen and Wiersema 2004, Hoetker 2007). Rather, it would be more informative and appropriate to estimate the marginal effects of interaction terms by setting meaningful values for the other variables in the model (Hoetker 2007). To estimate the marginal effects of the hierarchical changes on the division of innovative labor, we set the automaker dummy to zero and one, respectively, while constraining the other variables at their mean values. The marginal effects analysis indicated that the technology shift of the inclusionary hierarchy increased the probability of suppliers' component innovation and automakers' architectural innovation by 13.8% and 27.6%, respectively, confirming the interpretations based on the significance and signs of the interaction terms (see model 3). Similarly, the marginal effect analysis also confirmed that the emergence of a digital control hierarchy increased the probability of suppliers' architectural innovation (β_2; see model 4). However, the marginal analysis indicated that the architectural innovation associated with the digital control hierarchy increased the probability of automakers' component innovation by 8.9%. The results of the marginal effect analysis are summarized in Table 4.

In models 5 and 6, we replaced the automotive patent control variable (*Automotive patents*) with a general

Table 4 Propensity for Component (Architectural) Innovation by Automakers and Suppliers After Architectural Innovation in Inclusionary and Digital Control Hierarchies

	Automakers (%)	Suppliers (%)
Inclusionary hierarchy (1970–1993)	(27.6)	13.8
Digital control hierarchy (1980–1998)	8.9	(39.7)

economy-wide patenting (*Total patents*) to test the sensitivity of the regression models 3 and 4, respectively. In models 7 and 8, we tested the robustness of the regression results of models 3 and 4 against the unobserved heterogeneities by performing firm fixed-effects logit regressions.[10] The results of regressions and marginal effect analyses performed following models 5–8 consistently supported the major findings of this study.[11]

After a technological shift in the inclusionary hierarchy, automaker OEMs and component suppliers focus more on architectural and component innovation, respectively, which supports H1A and H1B (in accordance with the mirroring hypothesis). However, with regard to technological shift in the digital control hierarchy, automaker OEM propensity for component innovation increases together with the supplier propensity for architectural innovation, supporting H2A and H2B (in accordance with the systems integration perspective). Consequently, the "mirroring hypothesis" seems to hold for technological shifts associated with the inclusionary hierarchy, whereas the "systems integration" perspective holds for technological shifts in the digital control hierarchy.

Discussion

In their seminal work on the division of innovative labor, Arora and Gambardelli (1994) indicated that as knowledge associated with product innovation becomes increasingly abstract and generally applicable, barriers to innovation become dramatically reduced and more suppliers will innovate. This knowledge generalization can, in part, be facilitated by product modularity. Standardized interfaces between modules substitute for integrative, coordinating knowledge and offer a stabilized, explicit form of "advanced technological knowledge" (Sanchez and Mahoney 1996) to which suppliers can build competencies. Thus, the work on modularity further fulfills Arora and Gambardelli's thesis by offering an explanatory mechanism by which knowledge can become generalized.

Following this work on modularity and the division of innovative labor, Brusoni et al. (2001, p. 597) indicated that even for modular products, firms "know more than they make." Firm competencies, especially on the part of large OEMs, go beyond the products they actually manufacture, indicating that modular product interfaces are not perfect substitutes for many forms of advanced technological knowledge (Steinmueller 2003). Large OEMs need to maintain coordinating, integrative knowledge in order to produce their products, and researchers in this tradition offer a variety of explanations for when this is required (see Prencipe et al. 2003). Just as the work on modularity provided an explanatory mechanism for why suppliers are increasingly engaged in innovation, in this paper we offer an explanatory mechanism for why OEMs need to maintain competencies beyond the products that they manufacture: the widespread emergence of digital control systems in contemporary complex products.

Although our explicit emphasis on digital controls is new to organizational scholarship, examples of digital controls abound in the research. In particular, work that has questioned the modularity explanation analyzes contexts where digital controls take a central role. In domains as diverse as aircraft engine design (Brusoni et al. 2001, Sosa et al. 2004), computer design (Langlois 1997), and chip design (Ernst 2005), each has found that the mirroring hypothesis does not seem to apply. In all cases they argue that the division of innovative labor does not involve delegation of component knowledge to suppliers because OEMs need to maintain integrative and coordinating competencies in order to bring these complex products to market. Our explanation extends this observation. Because digital controls are increasingly important to complex products, it is precisely these digital controls that address much of that coordinating and integrating work within the complex products (Drouin et al. 1991). Furthermore, digital controls have an unpredictable, continuously evolving aspect that is not present in traditional electromechanical product structures.

Because of this unpredictable, continuously evolving aspect of digital controls, complex product structures are never completely stable from a functional perspective—including situations where there are stable modular interfaces between the physical components of the digital control system. Even if sensors and local control units may be stabilized over a period of time, there are two points of continuous change that persist in a digital control hierarchy that are typically not evident in a traditional electromechanical inclusionary hierarchy. The first involves software. Because digital controls are programmable, there is the ever-present opportunity to change and improve controls—even after the complex systems are in use (e.g., firmware updates). Second, there is always the possibility that integrative control units will be added further up the hierarchy that coordinate across ever-broader reaches of the complex system and integrate this complex system with other complex systems. In this sense, over time digital control systems become increasingly decoupled from the components they control (Findeisen et al. 1980).

As evolving decision systems (Mesarovic et al. 1970) that are simultaneously decoupled from the inclusionary hierarchy, yet also work to integrate that hierarchy, digital controls offer insight into the management and design of complex systems. One of the core precepts of complex systems theory is Ashby's (1958) law of requisite variety, which in essence states that the controller must have as much variety (or be as complex) as the system it controls in order to control that system adequately. Following Simon (1996), much of organizational scholarship is based on the observation that design complexity can be managed through partially decomposable subsystems, which involves reducing the complexity of the system under control by decomposing that system into manageable modules (see Baldwin and Clark 2000). However, with this focus on simplifying products, organizational scholars overlook the other strategy for attaining requisite variety: by increasing the complexity of the controller. With the radical innovation in speed, size, and reliability, digital systems can now dramatically expand the scope of automated control (Pop et al. 2004). Large-scale integrative control activities that in the past existed only in theory can now be realized in practice (Warwick and Rees 1988). Moreover, continued advancements in embedded technology and related standards enable unprecedented levels of data integration and convergence that can monitor and control increasingly diverse subsystems and components in real time (Yoo et al. 2010). These decoupled, integrative digital control hierarchies enable organizations to control an unprecedented level of complexity. Thus, to develop increasingly complex systems, organizational researchers can also think in terms of increasing the complexity of the controller through digital controls (that is, in addition to decomposition).

These observations about digital controls may explain why the systems integration perspective (Prencipe et al. 2003) has gained so much attention in recent years. In the past, the mirroring hypothesis (Brusoni 2008) was accepted as fact—and this view held well enough because control systems were tightly coupled with the components that they controlled. A single-product hierarchy was adequate for characterizing complex products, and product components were largely integrated through their direct interfaces with each other. Only in recent decades have digital control technologies matured enough to begin transforming industries. Now, given the broadly integrative capabilities associated with digital control hierarchies, researchers have begun documenting the transformations accompanying this revolution. This research provides a language for dealing with this particular form of digital innovation, as well as an initial explanation for the implications of digital control hierarchies on interfirm innovation. More importantly, however, this research explains how the mirroring hypothesis (e.g., Baldwin 2008) and the systems integration perspective (e.g., Prencipe et al. 2003) can be reconciled. Although these two views are often thought to be contradictory (Brusoni 2005), our research shows that they are both relevant, given a dual-product hierarchy view of complex products.

Implications for Practice

The practical implications of this research involve clarifying key capabilities that different firms might nurture given the increased role of digital controls in innovative activity around complex products. First, it is important to note that design practices associated with digital technologies are fundamentally different than those associated with traditional electromechanical complex products (Turner 1987, Whitney 1990), and certain organizations, particularly OEMs, may wish to proactively develop capabilities in software development. Product design and development firms rooted in traditional electromechanical logic follow linear or cascading development methodologies in designing complex physical systems (Ulrich and Eppinger 1995). In these firms, development problems typically involve managerial solutions or changes to intrafirm or interfirm structures (e.g., Clark and Fujimoto 1991). In contrast, software development requires firms to have the technical knowledge about fast-paced digital innovations and about a wide array of application domains (Curtis et al. 1988). This process of integrating multiple application domains with diverse sets of knowledge are one of the central issues that research on software development has explored for decades (e.g., Hirschheim et al. 1995). As such, the literature on software development may offer managers a number of ways to enhance their product design and development activities. For example, information systems scholars have detailed a number of methods and notations for executing design projects covering a range of topics specifically geared toward managing complexity, including risk mitigation (Lyytinen et al. 1998), user involvement (Mumford 2003), iterative development (Berente and Lyytinen 2009), design requirements (Hansen et al. 2009), and a variety of notations including object-oriented techniques (Booch et al. 2007).

In addition to building capabilities in domains such as software development, OEMs may wish to maintain capabilities in component design in order to more effectively integrate components through digital control systems. Although modular architectures are intended, in part, to relieve OEMs from the need to maintain certain component-level competencies, our research shows that this may not be the case to the degree that some scholars have argued. Instead, this work adds to the body of research that advises OEMs to maintain competencies in certain key components (Christensen 2006).

Of course, our analysis highlights how the strategies associated with relative efforts in component versus architectural innovation depend, to an extent, on an organization's position in the supply chain and the point in the evolution of the relevant product structures. Just as OEMs may increase their component innovation to best capitalize on a technological shift in the digital control hierarchy, their suppliers may want to move upstream and focus more on architectural innovation—even the innovations associated with digital controls—in order to position themselves for bundling multiple components together.

Our research does not address which forms of innovation firms should be pursuing and when, but we do highlight what they might expect before and after shifts in the inclusionary and digital control hierarchies. However, based on our theoretical lens, when innovating around the digital control hierarchy, OEMs need to maintain work across a variety of domains—digital technologies, architectural, and component level—because digital hierarchies span all of these realms. As products continue to become increasingly complex and digital control hierarchies continue to expand, it will be critical for OEMs to continue aggressively innovating at the component level to be prepared to capitalize on the never-ending stream of opportunities associated with digital technologies.

Future Research

Future research should do more to distinguish digital controls from other forms of digital innovation. In automotive contexts, for example, digital innovation is transforming the driver and passenger experience through multimedia entertainment and communication systems (Leen et al. 1999). Digital controls are already beginning to integrate with entertainment systems and other electronic subsystems, and it will be important to determine when and how we might distinguish digital controls from other digital systems. Beyond this, however, a variety of digital systems aid in integrating, coordinating, and controlling interfirm and intrafirm processes. For example, Brusoni (2005) looks at chemical processing as a (more or less) modular system, and the digital controls that span those modular practices may change the way such organizational practices are conceived. More research in the way different forms of digital controls might integrate across products and interfirm practices is also in order.

Furthermore, much of the research on the interfirm division of innovative labor generally positions the OEM in a privileged role in supplier networks, and our theorizing is no different. Future work should focus more on the impact of digital control innovation from a supplier perspective. For example, our finding that automakers have an central role in innovating after a technological shift in the digital control hierarchy seems to contradict the view of Henderson and Clark (1990). They argued that established firms are disadvantaged when new technological changes have digital-type innovation because of established firms' difficulty in switching to a new mode of learning that requires building new digital knowledge on existing digital knowledge base. However, we found that the OEMs led much of the digital control-related innovation. What does this mean to suppliers? Future research might reexamine the thesis of Henderson and Clark in the context of digital controls.

Future work should also address different system contexts in different industries and should include alternative measures for innovation. Also, it would make sense to relate these measures to organizational performance over time. Finally, some researchers have indicated that competitive forces and the division of innovative labor do not play out in all complex product development efforts in the same way (Argyres and Bigelow 2010). Certain complex systems are not subject to Schumpeterian market forces and are coordinated through powerful actors coming together to realize specific product designs in a way that does not reflect traditional competitive dynamics (Miller et al. 1995). Therefore, one might expect the relationship between architectural innovation and the division of innovative labor to perhaps be different in different contexts.

Conclusions

The digital revolution is transforming the way that firms innovate in a supply chain, and there is a growing body of organizational literature on the relationship between information technologies and the interfirm *process* of innovation associated with complex products (e.g., Argyres 1999, Majchrzak et al. 2000, Yoo et al. 2006, Boland et al. 2007). However, this is not the extent of the transformational effect of the digital revolution on innovative interfirm practices. Complex products themselves are increasingly made up of digital components, a trend that Yoo et al. (2010) refer to as "digital innovation," which emphasizes the digital elements of *product* innovation (in contrast to this work on information technology innovation that focuses on the *process* of innovation). In recent years, digital product innovations have brought transformative change to a variety of industries, including the music, film, and automotive industries (Yoo 2010). In this paper we add to the growing body of literature on digital technologies in *products* of innovation and in the associated effects on organization (Yoo et al. 2010).

Specifically, we extend the body of literature that attends to the relationship between complex product architectures and the division of innovative labor in the supply chain. Although recent research does identify the importance of the digital revolution to the way firms maintain their capabilities, none of the organizational literature specifically distinguishes the important class of digital technologies known as digital control systems. In emphasizing the importance of digital control systems in our work, we conceive of complex product architectures in terms of two product hierarchies: the inclusionary and the digital control hierarchy. Furthermore, we use this distinction to reconcile two competing views about the relationship between complex product structures and the interfirm division of innovative labor.

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Endnotes

[1]The general theory of Mesarovic et al. (1970) is rooted in cybernetic system theory and is concerned with generic coordination principles intended to be applicable to any complex system domain—from industrial and biological systems to organizations and societies. This work has been influential in process control engineering, operations research, complex systems, and computer science, and it has been leveraged much less often in research in information systems, economics, and social and organizational theories.

[2]Coding for both innovation-type and technology-choice variables was cross-checked by an independent coder.

[3]We also ran count-based negative binomial fixed-effects regressions to test the sensitivity of the model. The negative binomial fixed-effects estimator confirmed the key results. The results are available from the authors upon request.

[4]Patent counts for the individual top patenting firms are available from authors upon request.

[5]This research methodological approach of selecting a representative subset of a population, notably the major firms' data for analysis, is widely adopted in patent data-based studies (e.g., Rosenkopf and Nerkar 2001, Almeida and Kogut 1999).

[6]We used the Stata command by Collin to calculate the variance inflation factor for independent variables; none of them was higher than 10.

[7]The relatively high correlation between overall patenting in automotive technology and digital control hierarchy suggests that the digital revolution in the 1990s may account for the nontrivial influence on patenting activities in automotive technology. Correlation is also relatively high between regulatory expenditure and technology self-containment. This relatively high correlation supports the idea that high regulatory stringency may have influenced the innovation in auto emissions control.

[8]A similar result was observed for model 5 with the total patent control variable (β_{11}).

[9]$\beta_3 = (\textit{Effect on automakers}) - \beta_1$ in model 3, and $\beta_4 = (\textit{Effect on automakers}) - \beta_2$ in model 4.

[10]The OEM dummy variable is subsumed within the firm fixed effects and is therefore not shown in the specification for models 7 and 8.

[11]Results of additional marginal effect analyses for models 5–8 are available from the authors upon request.

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